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# Mechanics and assembly of the silicon vertex detector for the PHENIX experiment at RHIC

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## Abstract:

The PHENIX experiment at the Relativistic Heavy-Ion Collider explores the phase diagram of strongly interacting matter through collisions of beam of heavy nuclei. A second physics program addresses the spin structure of the nucleon through collisions of beams of polarized protons. The PHENIX apparatus has been particularly designed for lepton-pair measurements and comprises detectors for charged-particle tracking, particle identification, calorimetry and collision centrality monitors. Los mass detector systems and high-rate capability have been central to its concept. Recently a silicon vertex detector has been added to the experiment. It will extend the capabilities of PHENIX towards more refined studies involving heavy flavor physics with direct detection of decays. The presented article addresses technical aspects of the vertex detector's mechanical construction and the assembly of its components. It contains various detailed information and may be of interest to a larger scientific and engineering community in the fields of high –energy and heavy-ion physics.

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*Keywords:* RHIC; PHENIX; Vertex detector;

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## 1. Introduction

The PHENIX detector at the Relativistic Heavy Ion Collider is about to begin its twelfth year of physics. It is designed to perform a broad study of  $A$ - $A$ ,  $p$ - $A$  and  $p$ - $p$  collisions to investigate nuclear matter under extreme conditions.<sup>1</sup> The silicon vertex tracker barrel detector (VTX) will substantially enhance the physics capabilities of the PHENIX central arm spectrometers<sup>2</sup>. The prime motivation is to provide precision measurements of heavy-quark production (charm and beauty) in  $A$ + $A$ ,  $p(d)$ + $A$ , and polarized  $p$ + $p$  collisions. These are key measurements for the future RHIC program, both for the heavy ion program as it moves from the discovery phase towards detailed investigation of the properties of the dense nuclear medium created in heavy ion collisions, and for the exploration of the nucleon spin-structure functions. In addition, the VTX will also considerably improve other measurements with PHENIX detector system.

The addition of two Forward Silicon Vertex Trackers (FVTX) detectors will extend the vertex capability of the PHENIX Silicon Vertex Tracker (VTX) to forward and backward rapidity with secondary vertex capability in front of the two PHENIX muon arms<sup>3</sup>. Figure 1 shows a schematic representation of the PHENIX experiment at RHIC for the recently completed 2011 run.

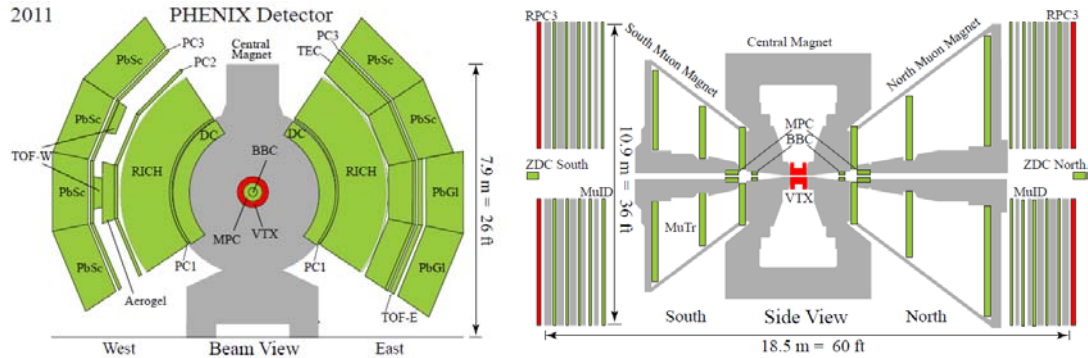


Figure 1: PHENIX Experiment at RHIC. The Z envelope for the VTX and FVTX detectors is 820.0 mm between the Central Magnet poles.

## 2. Design Criteria

The available space for the new Vertex Detector is limited by the existing Central Magnet, where there is only 800.0 mm between its pole tips. In preparation for the VTX barrel detector's installation for Run 11, (this past year), a new beampipe was also installed that covers the colliding beam interaction region. The new beampipe is 40.0 mm in diameter, with a wall thickness of 0.50 mm. This pipe was Non Evaporative Getter (NEG) coated prior to installation and bake-out. NEG coating has been used extensively in the LHC accelerator at CERN, and has proven to be an effective way to suppress electron mulitpacting in particle accelerators<sup>4</sup>.

The VTX Barrel Detector consists of 4 radial sensor layers. The inner two layers are comprised of silicon pixel sensors 200.0  $\mu\text{m}$  thick at radii of 25.5 and 50.4 mm from the beam axis. The pixels are 50.0  $\times$  450.0  $\mu\text{m}$ . These sensors were manufactured by Hamamatsu Corporation of Japan<sup>5</sup>. The pixel sensors are AC coupled to the LHCB1 readout chip<sup>6</sup>, which is bump bonded to the sensor. The outer two layers are at average radii of 110.0 and 160.0 mm. These layers make use of a novel Silicon sensor "stripixel" developed at Brookhaven National Laboratory's Instrumentation Division. This sensor incorporates two-dimensional position sensitivity with single-sided processing achieved by exploiting the charge sharing between two interleaved electrodes in one pixel<sup>7</sup>. Signals are read out by double layers of Aluminum strips. The sensor modules are 320.0  $\mu\text{m}$  thick and have an area of 35.0  $\times$  64.0 mm. The stripixel array is on a 80.0  $\times$  1000.0  $\mu\text{m}$  pitch. These sensors were manufactured by Hamamatsu Corporation of Japan<sup>5</sup>. This sensor is DC coupled and the readout makes use of the Fermilab SVX4 chip<sup>8</sup>. Because these sensors are DC coupled they must be operated in the range of 0° C, to limit the increase in leakage current from the radiation environment. Studies indicated that a single phase cooling circuit would meet the design requirement and 3M-NOVEC-7200 was chosen as the cooling medium. NOVEC HFE has superior environmental properties over traditional Fluorinerts, in addition to its heat transfer specification of 0.069W/m-K<sup>9</sup>. A sample of NOVEC 7200 was irradiated at the WNR Neutron facility at Los Alamos, to an integrated total dose of  $6.7 \times 10^{11}$  neutrons /cm<sup>2</sup> to test for the creation of free Fluorine radicals. The

sample was analyzed at 3M post irradiation and no increase in radical products were found compared to the non-irradiated sample<sup>10</sup>.

The barrel detector has an azimuthal acceptance of about  $2\pi$ . A CAD drawing for the barrel region is shown in Figure 2. The barrel assembly was designed to be in two halves that split at the beam axis for installation and servicing without disturbing the accelerator's beam vacuum.

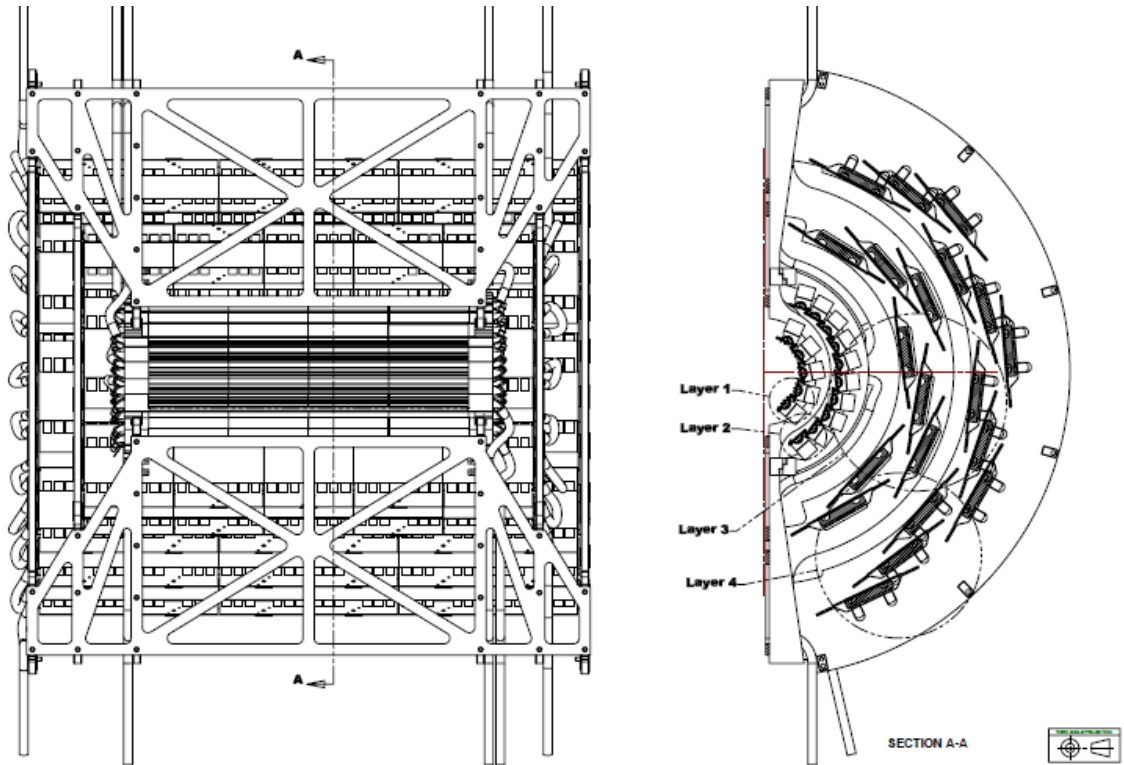


Figure 2: View of a half VTX detector barrel. The length is 406.4 mm, the total diameter is 436.2 mm.

### 3. Pixel Layers

The inner two pixel layers were designed to have a radiation length of  $\sim 1.2\%$  since these layers are the closest to the beam-pipe and adding multiple scattering into the outer two layers was not desired. A stave design was developed using Carbon composite materials, both for the thermal plane, to which the pixel sensor modules were bonded, and for the Omega shaped cooling channel that was bonded to the backside of the thermal plane. The bonded components that make up this stave assembly are shown in Figure 3.

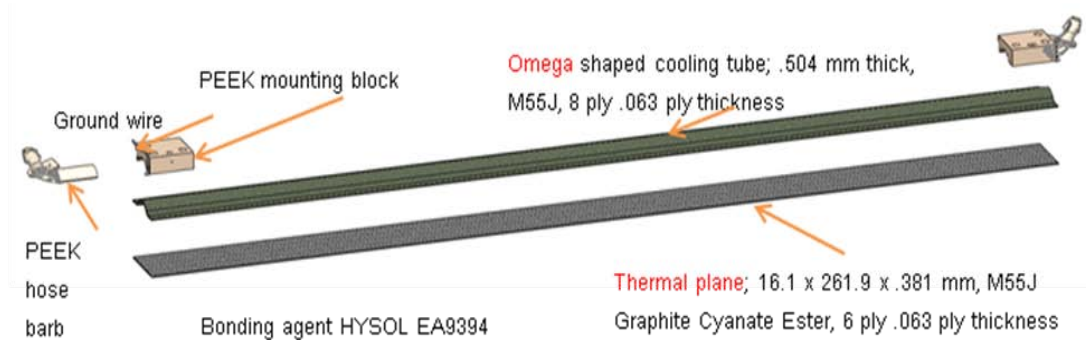


Figure 3: Bonded components for pixel staves of the barrel layers 1 and 2.

The assembly of these ladders was performed at RIKEN in Japan. A series of precision fixtures were used to locate the sensor modules on the bonded stave to better than  $10.0\ \mu\text{m}$ . Each ladder assembly has eight sensor readout chip pairs, where a bus attaches to four of these and is routed in opposite directions to readout electronics that are located in the end regions on large Aluminium cooling plates called “big-wheels”. The choice of M55J Graphite Cyanate Ester tape was made to fabricate the thermal plane and Omega piece because of its unit strength per weight<sup>11</sup>. The lay-up of this material is critical to maintain flatness especially after bonding. PEEK material was chosen for the mounting blocks and cooling connection barbs because of its radiation hardness and structural stability. The ladder assembly meets a flatness tolerance of  $100.0\ \mu\text{m}$ . These stave assemblies were fabricated at Lawrence Berkeley National Laboratory’s composite shop. Figures 4 and 5 show a Pixel ladder assembly and half ladder assembly.



Figure 4: Assembled pixel ladder in support frame, bus side up.

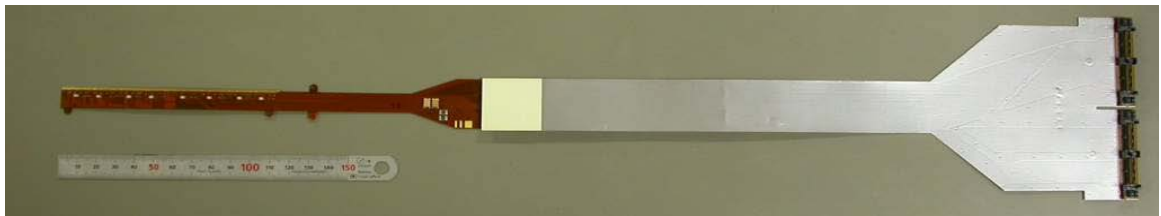


Figure 5: Half pixel assembly with bus and extender cable that connects to read-out electronics card, total length 60.0 cm.

#### 4. Stripixel Layers

The outer two layers of the VTX barrel detector use the BNL stripixel sensor. There are five sensor modules per ladder on layer 3 and six sensor modules per ladder on layer 4 ladders. As shown in Figure 2

there are 8 ladder assemblies in a layer 3 half detector and 12 ladders in layer 4. The ladders are offset in the radial direction to facilitate the sensor readout. The SVX4 readout chips are on the same side of the ladder as the sensors, while the bus is mounted on the backside of the stave. The interconnection between the top side and the bottom makes use of PariPoser anisotropic conducting material<sup>12</sup>. This material was designed for fine-pitch, high-density interconnectivity with excellent thru-conductance and high in-plane electrical isolation.

The Stripixel ladders were designed to allow for individual electronic/sensor modules and a bus to be mechanically attached to the stave, not bonded. An exploded view showing the construction of the stave is shown in Figure 6. The Stripixel stave is a sandwich assembly consisting of two face-sheets of K13D2U Carbon tape<sup>13</sup>, 0.063 mm thick, in a 6 ply layup with EX1515 Cyanate Ester resin. The core of the stave consists of an Aluminum cooling tube,  $3.18 \times 6.35 \times 0.38$  mm wall bonded in Allcomp K3 Carbon foam core<sup>14</sup>. The assembled stave is bonded using Hysol EA9396 epoxy, in a fixture that holds the assembly flat to  $100.0 \mu\text{m}$ . The circular inserts, hose barbs and one end block are made from PEEK. The other end block is made from Aluminum in order to ground the ladder assembly. These stave assemblies were also fabricated at the Lawrence Berkeley National Laboratory's composite shop.

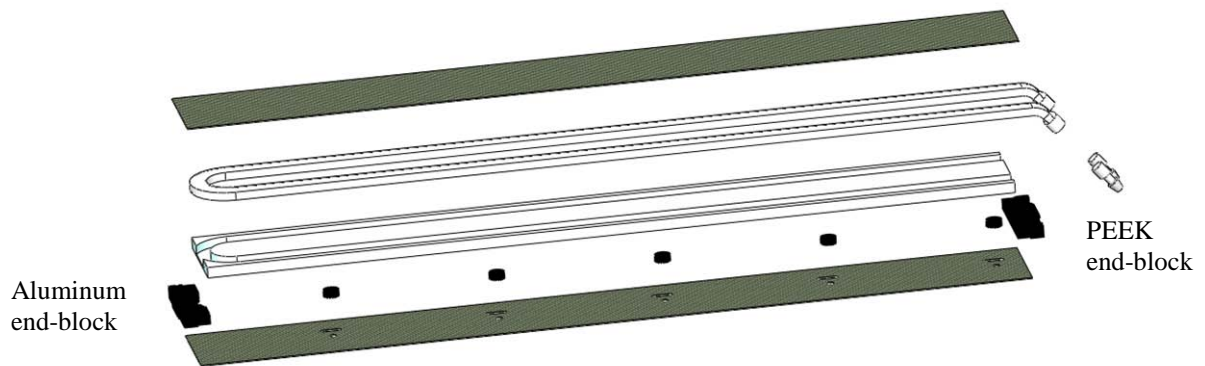


Figure 6: Exploded view of layer 3 Stripixel ladder stave.

## 5. Analysis

Mechanical and thermal analyses were performed on both the pixel and Stripixel stave designs using the Nastran Mat9 software analysis software<sup>15</sup>. The data from this analysis is shown in Figure 7. For the Pixel ladder the  $\Delta T$  was  $11.5^\circ\text{C}$  with a sag due to gravity  $< 2 \mu\text{m}$ . If an Aluminum cooling tube were used in the Pixel stave assembly the  $\Delta T$  would increase to  $23^\circ\text{C}$ . The design goal for the Stripixel ladder was to keep the DC coupled sensors at  $0^\circ\text{C}$ . The bulk fluid temperature was at  $-6^\circ\text{C}$  and the peak temperature for the Read-out electronics was at  $3.2^\circ\text{C}$ . The temperature rise between the coolant and the Silicon sensor was  $5.5^\circ\text{C}$ .

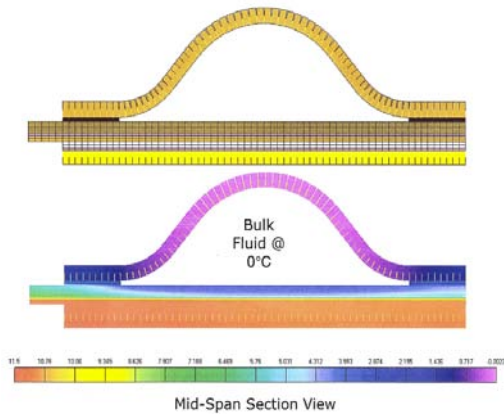


Figure 7a: Pixel stave analysis.

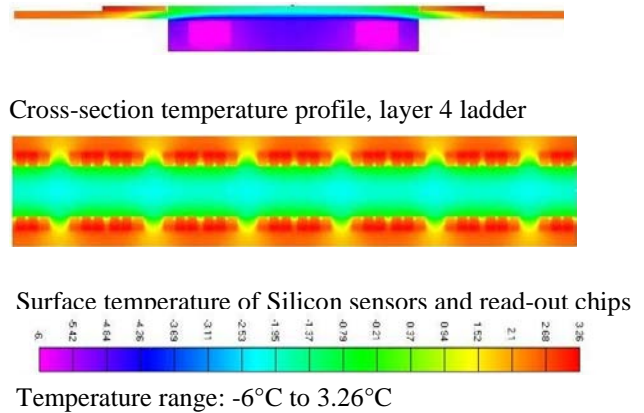


Figure 7b: Stripixel stave analysis.

## 6. Space-frame

The space-frame is constructed to mount the 4 separate layers of the barrel detector into a precision Carbon composite shell. This shell is made from layers of CN60 carbon cloth<sup>16</sup>, 1.5 mm thick and it is attached to six barrel mounts. The barrel mount assemblies are a sandwich of M55J carbon fiber tape with Allcomp K3 Carbon foam as the core material. Each barrel mount panel is 6.3 mm thick. A center vertical gusset is used to tie the other side of the barrel mounts together and help stabilize the half-barrel assembly. Each half space-frame assembly is mounted via three flexures to a rail system that allows the two half detectors to open from the beam-pipe. The two half detectors align to each other using a three point kinematic mount system. Figure 8 shows an exploded view of a half barrel detector space-frame assembly.

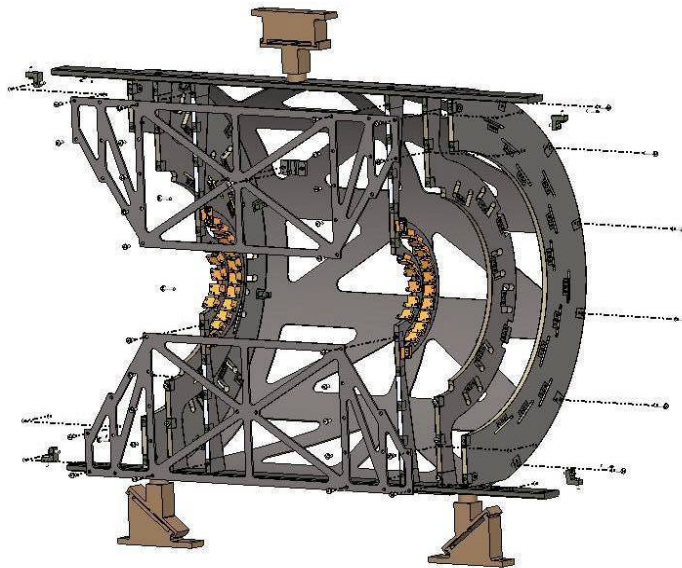


Figure 8: Exploded view of VTX half barrel-detector space-frame assembly



A separate set of mounts support the read-out electronics for the barrel detector, at each end of the space-frame assembly. These electronic cards are attached to a set of Aluminum half disks that also serve as thermal transfer heat sinks. A cooling line runs around the outer perimeter of each plate carrying NOVEC-7200. These plates are a part of a detector gas-enclosure that consists of a FR-4 cylinder with bonded FR-4 half-disk plates at both end, and a aluminized Mylar window over the acceptance region to the experiment's central arms. This gas enclosure is mounted to the same rail system as the detector but from different mounts in order to prevent the strain introduced by cables and cooling lines from interfering with the detector's position.

Figure 9 shows an assembled half VTX barrel detector with one of the FVTX end caps installed and the second one in an exploded view. The full FVTX detector consists of sixteen half station disk. Each station disks has Silicon mini-strip sensors that are shaped in pie segments, covering 7.5 degrees of azimuthal acceptance. The mini strips have 75.0 micron pitch in the radial direction. Each of the wedge assemblies comprises a 15.0 degree opening angle, so wedges need to be mounted on both sides of a station disk to allow hermetic coverage of the 7.5 degree sensor. Each silicon sensor is comprised of two independent rows of mini-strips that are independently read out by chips on the left and right side of the wedge. The readout chips are named the FPHX chip and they were custom developed in collaboration with the ASIC design team at Fermilab<sup>17</sup>. Kapton flex circuit readout cable connects the wedge to the readout electronics mounted on the FVTX Aluminum "big-wheel".

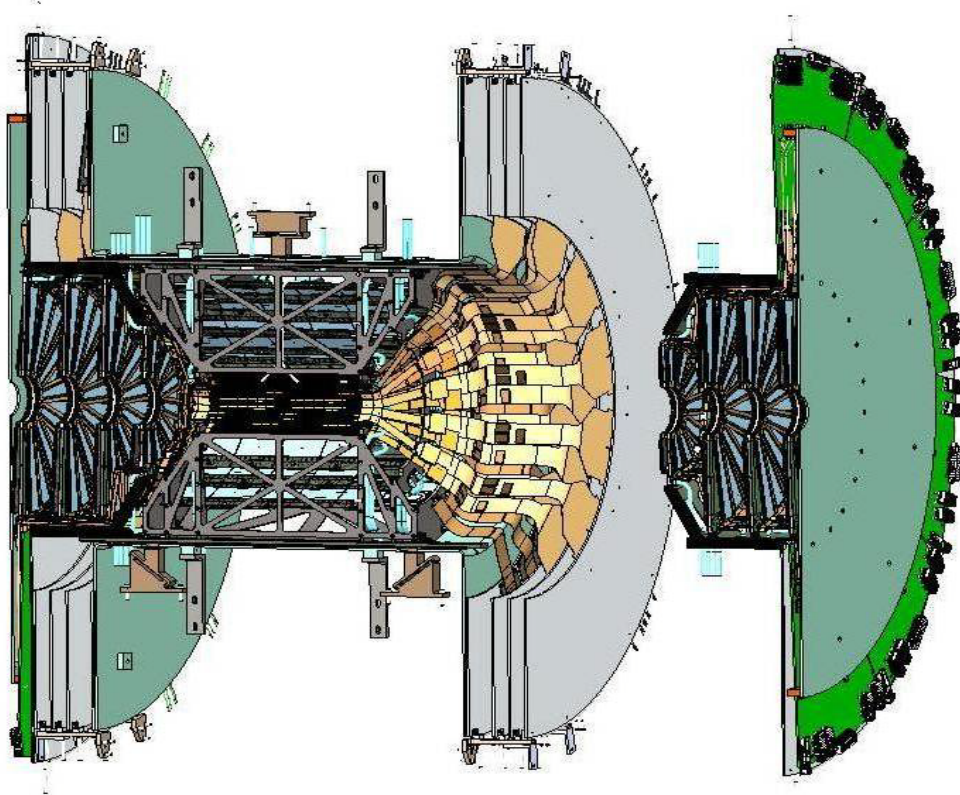


Figure 9: VTX half barrel detector assembly with the gas enclosure an both FVTX half detectors.





Figure 10: FVTX half disk assembly.

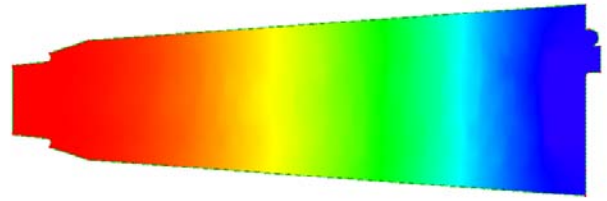
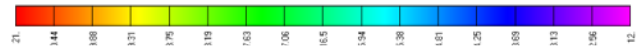


Figure 11a: Thermal analysis of large wedge.



21.°C

16.°C

12.°C

Figure 11b: Temperature scale for thermal analysis shown

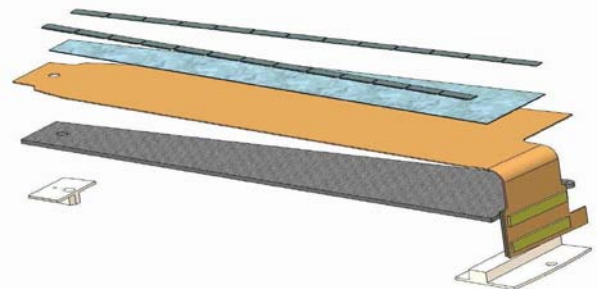


Figure 11c: Exploded view of a wedge assembly.

## 7. FVTX

The FVTX wedge is a laminated sandwich assembly. The sensor assembly is made up of a 334.0  $\mu\text{m}$  thick high density-interconnect (HDI) cable that has the 320.0  $\mu\text{m}$  thick silicon sensor, manufactured by Hamamatsu Corporation of Japan<sup>5</sup>, and FPHX readout chips bonded to it. The sensor assembly is then bonded to a 1.56 mm thick Carbon backplane, made from K13D2U tape and EX1515 resin. The bonding agent used for this assembly is 0.05 mm thick Arclad 8026 adhesive transfer tape<sup>18</sup>. Pedestals made of POCO Graphite are used to stand off the wedge assemblies from the surface of the station disks. These pedestals allow for two levels of wedges on the surface of a half disk as can be seen in Fig. 10.

Figures 11a and 11b show a thermal analysis of the wedge assembly where a  $\Delta T$  on a wedge is  $\sim 7.47^\circ\text{C}$ . Heat from the FPHX read-out chips must pass through the HDI into the Carbon thermal plane then into the POCO Graphite spacer block to the station-disk where NOVEC 7200 flows around the outer perimeter in a channel. There is a delta T of  $\sim 8.0^\circ\text{C}$  from the bulk coolant to the wedge. A constraint on this analysis was set so the peak temperature on the FPHX chips was at  $21^\circ\text{C}$ . Figure 11c shows an exploded view of a FVTX wedge assembly. The station disks were constructed using face sheets of K13C2U uni-fiber 0.4 mm thick with PEEK outer and inner rings and PEEK bobbins in the middle to maintain a uniform thickness for the assembled panel. The FVTX disks are mounted in a Carbon composite shell made from CN60 cloth, similar to the space-frame. The shell is precision machined in a

CNC machine at the LBNL facility as well as having the assembly CMM in a Zeiss touch/optical coordinate machine that identifies the location of each disk in each shell assembly to 10.0 micron precision. After a station disk has its wedges attached to it this assembly is measured by another optical CMM facility that looks at 100.0 micron targets that are included in the mask of each Silicon sensor. These measurements have a resolution of 5.08  $\mu\text{m}$  in X-Y or the face of the sensor and 12.27  $\mu\text{m}$  in the Z direction<sup>19</sup>.

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